SW231

Geospatial Modeling Suggests Threats from Stormy Seas to Rhode Island's Coastal Septic Systems

Alissa H. Cox[1], Matthew J. Dowling[2], George W. Loomis[3], Simon E. Engelhart[4], Jose A. Amador[5]

[1]Department of Natural Resources Science, University of Rhode Island, 1 Greenhouse Rd, Kingston RI 02881, USA; alibba@uri.edu (corresponding author)

[2]Town of Charlestown, RI, Wastewater Management Division, 4540 South County Trail, Charlestown RI 02813, USA; mdowling@charlestownri.org

[3]New England Onsite Wastewater Training Center, University of Rhode Island, 1 Greenhouse Rd, Kingston, RI, USA; gloomis@uri.edu

[4]Department of Geography, Durham University, South Road, Durham DH1 3LE, UK; simon.e.engelhart@durham.ac.uk

[5]Department of Natural Resources Science, University of Rhode Island, 1 Greenhouse Rd, Kingston RI 02881, USA; jamador@uri.edu

Abstract

Coastal communities preparing for climate change and sea-level rise need to consider the impact large storms will have on below-ground infrastructure. Although these communities often rely on onsite wastewater treatment systems (OWTS) to treat wastewater, there is little research describing how these systems might be impaired after a large storm. A GIS-based model was used to examine the potential impact of storms (1-in-25 to 1-in-500 year events, category 1-4 hurricanes) on OWTS along the southern Rhode Island shore. Based on geographic location, coastal geologic setting and proximity to coastal features, the number of OWTS threatened by wave inundation and storm surge ranges from ~2,000 in a category 1 hurricane to ~3,000-3,800 in major flood events, to over 4,600 from a category 4 hurricane. The number of affected OWTS increases by ~200 if 0.3 m of sea level rise expected over the next 30 years is considered. Damages incurred can cost homeowners from $1,000 to >$30,000.

Compromised systems will also threaten human and environmental health, as untreated wastewater enters ground and coastal waters. Methods from this study can be applied to improve coastal communities' resilience planning globally.

Key Words: septic system; onsite wastewater; storms; coastal hazards; hurricanes; inundation; coastal flooding; flood events; wastewater treatment; disasters; modeling; GIS; coastal resilience; coastal planning

Introduction

Coastal New England communities are projected to bear the brunt of many of the adverse effects of climate change. While predictions for sea-level rise (SLR) are still being refined for the region (range: 0.4 to >3m by 2100 for southern New England Coast (NOAA et al. 2017); 0.07 to 0.45 m by 2050 in Newport, RI (US Army Corps of Engineers 2019; Fig. S1), coastal residents must also consider threats from other hazards, particularly large storms events, which will compound the effects of SLR. Future storms are predicted to be more intense and have larger-scale impacts along the New England coast than storms striking the region today (Karegar et al. 2017; Kopp et al. 2014; Lin et al. 2016; Little et al. 2015; Marcos et al. 2019). Large storms are associated with high winds, intense precipitation, strong ocean waves and currents, and storm surges, which can cause significant damage to properties along the coast. In southern Rhode Island (RI), properties located on barriers, headlands and coastal lagoons have been affected by storms in the past. For example, in October 2012 Superstorm Sandy left RI coastal communities with over $11.3 Million in storm-related damage (Ostiguy et al. 2018).

In the aftermath of these storms, media and government organizations tend to focus on the impact to above-ground structures, with little thought given to critical below-ground systems like onsite wastewater treatment systems (OWTS, i.e. septic systems) and potable wells. During storm events, marine inundation and/or elevated groundwater tables (caused by precipitation and/or temporary rises in sea level) result in reduced unsaturated vadose zones below drainfield components, compromising nutrient attenuation and pathogen removal (Cooper et al. 2016; Humphrey et al. 2017; O'Driscoll et al. 2014). Once OWTS are compromised, groundwater and coastal waters are impacted by nutrients and pathogens from untreated wastewater (Cooper et al. 2016; Humphrey et al. 2011, 2013; Lusk et al. 2017). These impacted waters become a pressing concern for both human and ecosystem health (Cooper et al. 2016; Fisher et al. 2016a). While the vulnerability of coastal large-scale centralized wastewater treatment plants has been recognized, prompting retrofits to protect them from storm events and SLR (Fisher et al. 2016b; Foster 2015; Hummel et al. 2018; Takamatsu et al. 2015; Woodard & Curran and RPS ASA 2017), OWTS have been overlooked despite their widespread use in coastal communities. Though some studies examined emerging contaminant loads from OWTS in waterbodies along the mid-Atlantic coast after Superstorm Sandy (Fisher et al. 2016a), and assessments of OWTS vulnerability to SLR exist for Miami-Dade County (Miami-Dade County Department of Regulatory & Economic Resources et al. 2018), to the authors' knowledge, little research has been published assessing wide-scale impacts on OWTS from storms affecting the south-facing shores of New England, nor are there guidelines available to help improve their resiliency to future flooding or coastal storm events.

To predict and understand the risks coastal RI communities face in light of climate change, models and geographically-referenced map components have been developed since Superstorm Sandy to forecast the extent to which SLR and storm events are likely to impact coastal areas (RIGIS 2017a). A regional probabilistic Coastal Environmental Risk Index (CERI) assessment has been developed to model above-ground structural damage to coastal buildings (Spaulding et al. 2016), but this model does not predict duration of flooding, nor does it assess damage to below-ground infrastructure like OWTS. Nearly all homes along the southern RI coast rely on individual OWTS to treat domestic wastewater (Cox et al. 2019). Given that OWTS drainfields require unsaturated conditions to function properly (Amador and Loomis 2018), accounting for the temporal dynamics of the inundation events mapped by the aforementioned tools is critical to understanding how coastal OWTS are likely to be impacted by such events.

Coastal flood events have the potential to disrupt and permanently damage OWTS in a variety of ways. Inundation for several days could raise groundwater tables enough to dislodge buoyant septic system components lacking adequate anti-floatation measures, disrupting the elevations of gravity-fed systems (Scherer 2019; USEPA 2017). Coastal groundwater tables can rise between 0.3 to 1 unit of elevation for every unit of sea level rise (Miami-Dade County Department of Regulatory & Economic Resources et al. 2018; Sukop et al. 2018; Walter et al. 2016). Floodwaters and elevated groundwater tables can also impair the drainfield's ability to adequately treat wastewater before it is discharged to groundwater (Van Dolah and Anderson 1991; Mallin and Corbett 2006; Scherer 2019; USEPA 2017). Air-filled or above-ground septic system components might be also damaged, filled with sediment or dislodged from surrounding soils by fast-moving floodwaters and associated scouring (Heger and Anderson 2017; Scherer 2019; USEPA 2017). Electrical control panels for advanced treatment OWTS may be damaged by storm surge inundation, rendering these systems inoperable after waters recede (Scherer 2019).

To address the gap in the understanding of how storm events are likely to impact the functioning of coastal OWTS, this study combines inundation maps for storms of different magnitudes with maps detailing the locations of OWTS along the southern RI coast. The combination of these two data sets was used to develop a model that predicts the number of OWTS likely to be impacted by storms of different magnitudes and recurrence intervals. Predicting the number of OWTS along the south shore of RI that could be impaired, and the extent of damage, will be critical for coastal community resilience planning, and may lead to better integrated regulations to protect the region's drinking water and coastal resources.

The likelihood of septic system impairment was modeled as a function of location and elevation (a proxy for the duration of inundation, as there is no available data describing inundation durations in this context) to quantify the number and extent of systems that are impaired by different storm conditions. For each storm type, the severity of impact on a particular region of the coast is categorized: "serious", systems requiring major repairs or replacement, or catastrophic failure; "moderate", systems requiring minor repairs, short-term impairment; or "ephemeral", systems unlikely to incur any consequences, little impact. Maps were used to display spatial patterns of damage to OWTS, as well as the number of OWTS in each impact severity category. The model's assumptions were tested by comparing predictions for impacts to individual OWTS using the flood extent mapped for Superstorm Sandy (2012) to actual recorded field observations of damages to OWTS collected by town and RIDEM officials in the aftermath of the storm. The model's assumptions were then adjusted to better reflect the observed patterns of damage. Finally, the implications for coastal community resilience planning and future storm events are discussed.

The results of this study are intended to provide coastal New England communities, stakeholders and government officials with information to help inform resiliency planning and wastewater-related regulations over the coming decades. Other regions of the East Coast, including Florida, South Carolina and North Carolina are facing increased frequency and severity of storm events, coupled with sea-level rise, threatening wastewater treatment (Allen et al. 2018; Hummel et al. 2018; Little et al. 2015; Miami-Dade County Department of Regulatory & Economic Resources et al. 2018). This phenomenon extends beyond the US East Coast (Hallegatte et al. 2013; Neumann et al. 2015; Woodruff et al. 2013), and many other coastal communities across the globe can apply these modeling methods to assess the risks storms and flood events pose to their near-shore onsite wastewater treatment infrastructure.

Methods

Identifying OWTS in the southern RI region

To model the possible impacts of different storm events on OWTS along the south shore of RI, maps of storm-related OWTS damage patterns were created in ArcMap version 10.7. Table S1 shows the source of the shapefiles and data incorporated into the models. To identify properties using OWTS, tax assessors' property parcel map shapefiles from Westerly, Charlestown, and South Kingstown, RI were cross-referenced with parcels containing buildings (data used by 911 operators; RIGIS 2017b) in ArcMap. Properties within 61m (200ft) of a sewer line were excluded, since homeowners are required to tie into existing sewers in these areas (RIDEM 2018a). Narragansett was omitted from this analysis, as it does not provide geo-referenced parcel maps and is largely served by sewers along the coast, rather than by OWTS. In Westerly, RI, an estimated 6,043 parcels rely on OWTS, while in Charlestown and South Kingstown 4,824 and 6,856 parcels, respectively, rely on OWTS (Fig. 1).

Mapping flood extents for different storm categories

Inundation maps supplied by Rhode Island Geographic Information System (RIGIS) were used to estimate areas of projected storm surge flooding by various storm frequencies (RIGIS 2016a; b; Table S1). These simplified flood maps were created by scaling the relationship between water level and return period at a NOAA water level gauging station, using both the NOAA SLOSH model and the US Army Corps of Engineers ADCIRC/WAM/STWAVE models to scale the inundation for varying return periods in RI's coastal waters (Cialone et al. 2015; Spaulding et al. 2015). Modelled events include storms with a recurrence probability of 1-in-25-years (25-Y), 1-in-50-years (50-Y), 1-in-100-years (100-Y) and 1-in-500-years (500-Y). Additionally, modeled flood effects of "worst-case" scenarios of hurricane categories 1 through 4 were included in the analysis, although it is important to note that these hurricane categories are delineated by wind speed rather than storm surge or wind-driven wave parameters, which are often underestimated (Marcos et al. 2019). A SLR of 0 m is used to model current risk, and a SLR of 0.3 m (1 foot) is used to model risk in the next 30 years (NOAA et al. 2017; US Army Corps of Engineers 2019). Details regarding the different modeling parameters and assumptions used to create the inundation maps can be found in RIGIS (2017) documentation and in Table S1. Intersect functions in ArcMap were used to identify the total number of parcels affected by modeled flood events, while the average elevation (based on 60 cm (2 foot) contour lines) of each parcel was incorporated to categorize the severity of impact on OWTS along the coast, relative to the mapped flooding. Average, rather than maximum or minimum elevation, was used because buildings on coastal properties in RI are often required to be as far inland as possible to meet setback requirements from coastal features (RICRMC 2018), and thus are likely to be located at the highest elevation on the property. Properties on the barrier beach are located landward of the dunes, which may be up to ~4 m (14 ft) higher than the minimum elevation on the parcel, and thus unlikely to be located on the highest elevation on the property. Since many OWTS are conventional gravity-fed systems, their location is likely to be near the footprint of the building at the assumed average elevation of the parcel.

In addition to the above-mentioned storm conditions, the effects of storms (25 Y, 50Y, 100 Y) given 0.3 m (1 ft) of SLR were modeled along the southern RI coast, using

RIGIS-supplied inundation polygons with SLR for this purpose (RIGIS 2016a; Spaulding et al. 2015; Table S1). This value was selected based on SLR projections for the area for the next 30 years (given the IPCC global intermediate model (IPCC 2013), and the northeastern US being disproportionately affected by Antarctic ice sheet melt and slowing of the Gulf Stream (Sweet et al. 2017)), a time frame which has less uncertainty than predictions farther into the future. This time span also represents a typical mortgage period for the US, which is important from a homeowner's perspective: a homeowner is likely to assume that his or her investment in a structurally sound property and its infrastructure will not require additional substantial costs, such as a new septic system, over that time period. The effects of these storms combined with 0.3 m of SLR were modeled on present-day septic system distribution maps – no additional buildings were added to the analysis, despite current regionally high development of new homes in the area (RIGIS 2012).

Modeling impacts to OWTS

Impact categories to OWTS were developed based on observations by experts in the OWTS profession in the region, and the authors' projected impacts to systems are based on OWTS' geospatial position relative to Block Island Sound and tidally-influenced coastal lagoons (Fig. 1). All OWTS on properties directly on Block Island Sound were categorized as "Seriously" affected, as these properties are exposed to direct storm surge and wave action from the ocean during storms. Properties whose mean elevation based on the 60-cm (2 foot) contours was less than 1 m were also included in the "Serious" category, since OWTS in the lowest-lying elevations along the coast were projected to be the most impacted by storm surge and flooding, as they are likely to be the first to flood, and the last to see receding flood waters. Because these systems face exposure to flooding (lasting up to several days) and quickly moving water, the systems are unusable during the flooding event, and subsequent failures and/or permanent damage to system components are quite likely. Damage to the system can arise from scouring action of fast-moving water surges, in addition to electrical short-circuiting in advanced treatment systems required along certain areas of the coast (RIDEM 2018), and movement of air-filled system components in response to buoyancy in flooded soils, resulting in the misalignment of important components whose relative elevations are critical for proper system functioning.

Impacts to systems on properties whose mean elevation was 1 to 2.5 m was categorized as “Moderate” and impacts to systems on properties with mean elevation greater than 2.5 m was categorized as “Ephemeral”, based on expected duration of flood events and flood water velocities. Systems built in intermediate elevations (“Moderate” category) are expected to be affected by mid-term duration of low to medium energy inundation events, rendering systems temporarily unusable, but likely to recover after the storm event passes. These systems might require minor repairs or readjustments after the flooding has receded, but the likelihood of serious damage is slim. Systems at the highest elevations (“Ephemeral” category) are subject to the shortest length of inundation with low-energy waters, and thus are likely to suffer few effects from temporary flood waters as they recede and/or percolate down through the soil profile. Thus, these systems are expected to have few if any performance issues post-flooding.

Immediately following Super Storm Sandy in 2012, personnel from the Town of Charlestown, RI conducted comprehensive visual OWTS inspections on all parcels affected by the storm surge and developed a damage assessment ranking criteria summary. The RI Dept. of Environmental Management (RIDEM; Peter O’Rourke, personal communication, 2019) conducted visual observations of impact in Westerly. Notably, for many OWTS on low-lying parcels abutting Block Island Sound (Atlantic Ocean; Fig. 1) typically sited on the coastal barrier complexes, visual inspection revealed that Superstorm Sandy seriously damaged systems, requiring immediate repairs or replacement to restore OWTS function. Because RIDEM relaxed the requirements of its usual repair permit application process after Superstorm Sandy caused widespread damage along the southern RI coast in October 2012 (RIDEM 2012), there is little information available to assess which systems were repaired to what extent. The only publicly available RIDEM-tracked information is for properties on which OWTS were catastrophically affected by the storm, and required applications for temporary holding tanks to collect household wastewater. This corresponds to a total of 18 systems for South Kingstown, Charlestown and Westerly, RI (Peter O’Rourke, personal communication, 2019).

Table 1 combines projected impact category parameters with descriptions of observed damages to OWTS in Westerly and Charlestown, RI after Superstorm Sandy affected the southern RI coast in 2012.

Testing the model with data collected post-Sandy (2012)

To test the model, comparisons were made between predicted damage to OWTS along the coast based on the model and flood maps specific to Superstorm Sandy in 2012 (Fig. S1), and actual field observations of the damage to systems made by Charlestown town officials and RIDEM personnel (Peter O'Rourke, personal communication, 2019) after Sandy affected the southern RI coast in 2012. Notes for each property were coded for damage corresponding to "Serious", "Moderate" or "Ephemeral" effects on the system (see Table 1 for examples of damage descriptions).

To assess the model's performance, the modeled predictions for a particular parcel's impact category were compared to the damage category based on the field observations described above.

Results & Discussion

Modeling storm impacts on systems along the coast

The extent of flooding under current conditions along the southern RI coast varies by recurrence interval and hurricane category (Fig. 2). Properties facing Block Island Sound, and nearby low-lying parcels are likely to incur the most severe damage to OWTS during a storm or flood event. However, patterns of impacts to OWTS show that low-lying areas north of coastal lagoons may be as vulnerable as some properties closer to the ocean (Fig. 2 and Fig. 3), based on projected flooding and mean parcel elevation. The total number of flooded OWTS ranges from 2,037 to 4,632 for category 1 and 4 hurricanes, respectively, and 3,059 to 3,852 for 25-Y and 500-Y flood events, respectively (Table 2). These ranges represent 11 to 26% of the region's 17,723 OWTS affected by hurricane-associated flooding, and 17 to 21% of systems affected by floods characterized by recurrence interval. Compounding flood events with a projected 0.3m of SLR increases the total number of flooded systems by ~200 (Table 2). Increasing sea level mainly results in a larger number of ephemerally affected OWTS, since flood events with greater recurrence intervals result in higher elevations being exposed to flooding. The lower-lying parcels in the “Serious” and “Moderate impact categories experience flooding fairly uniformly, regardless of the recurrence interval. However, the model does not take into account the changing nature of recurrence intervals in the future under a changing climate, and thus represents a conservative estimate.

The model suggests that, except during a Category 1 Hurricane, the same 441 parcels are “seriously” affected by any given storm or flood type (Table 2). For any given flood event, 4% of flooded OWTS are likely to be seriously affected, while 1% are likely to face moderate damage. The proportion of ephemerally affected systems rises with increasing recurrence interval flood events, from 61 to 93% for 25-Y and 100-Y storms, respectively. These results also suggest that between 1 and 5% of flooded OWTS are likely to require repairs after a significant flood event strikes the coast, in addition to any above-ground structural damage sustained.

Comparing the model with data from Superstorm Sandy (2012)

Based on Superstorm Sandy flood maps (RIGIS 2016b), 2,334 parcels with OWTS in southern RI (excluding Narragansett) were inundated in 2012. Field notes describing visual damage to 153 systems taken by officials from the town of Charlestown after Superstorm Sandy struck the southern RI coast paint a ghastly picture: OWTS on properties facing Block Island Sound had all been subject to near-catastrophic damage from the storm (Fig. 4). Properties along the back barrier region of the barrier beach complex incurred moderate to serious damage to septic system components, depending on elevation (lower elevations had more severe damage). Properties at higher elevations, farther inshore were less affected, many showing little if any visible damage during above-ground assessments made by town officials (Fig. 4 A, B). RIDEM personnel observations of 230 systems along the coast of Westerly, RI show a similar trend. Many of the low-lying properties directly along the southern coast were damaged extensively, while homes bordering coastal lagoons and at higher elevations had less visible damage in the aftermath of Superstorm Sandy (Fig. 4 C, D). This is likely to be partly a function of water velocity; once water enters the coastal lagoon, it slows and perhaps results in slower and/or less turbulent flooding, which may be less disruptive to system components. It is also unclear why some systems in close proximity, with similar elevations could be affected to different degrees (Fig. 4 D, bottom). It is possible that system type accounts for this pattern of damage: notes from officials indicate that advanced treatment systems with highly engineered at- or above-grade components suffered more obvious damage than conventional systems with exclusively below-ground components. Microtopography may also be an important factor, directing the flow of precipitation and storm surge in ways that are not accounted for in the model.

A total of 383 parcels along the southern RI coast were assessed in person by either Town of Charlestown officials or RIDEM personnel, representing approximately 15% of all the parcels modeled to have been affected by Superstorm Sandy. Of these, 345 were incorporated into testing of the model. Modelling predicted that, of these 345 parcels, 25 would be subject to “Serious”, 18 to “Moderate” and 301 to “Ephemeral damage (Fig. 4, top portions of each panel). Based on field observations, 44 systems sustained “Serious” damage, while 39 and 245 systems sustained “Moderate” and “Ephemeral” damages, respectively (Fig. 4, lower portions of each panel). Field notes for 16 properties describe the damage as “Unknown” (Fig. 4 C, D; lower portions of each panel). Comparing these estimates to actual field observations indicates that the model correctly predicted the damage to 68% of the systems, underestimating damage 20% of the time, and overestimating damage 7% of the time (Fig. 4, Table 3).

The model results presented here resulted from substantially changing initial assumptions. First, instead of automatically categorizing every parcel bordering Block Island Sound as “Serious”, the impacts were fine-tuned based on observed patterns, to include some elevation cutoffs in this area of the coast. The model performed best when impacts to properties bordering the Sound were categorized as “Serious” for parcels whose mean elevation is less than 2 m, and “Ephemeral” if the elevation exceeds 2.4 m, with “Moderate” impacts falling between these values, and when the elevation cutoffs were changed to <1 m for “Serious”, 1 – 1.2 m for “Moderate” and >1.2 m for “Ephemeral” damage in properties not abutting Block Island Sound (Table 1).

Another important consideration is that current RIGIS predictions for coastal storm events tend to underestimate recurrence intervals by as much as twofold, and often fail to take the cooccurrence of SLR, storm surge and wind-driven wave activity into account (Little et al. 2015; Marcos et al. 2019). The model estimates that the number of systems affected and requiring repairs ("Serious" or "Moderate" impacts) is ~250 for all storm conditions. Since the model underestimates damage up to 20% of the time (Table 3), it is likely that the number of systems requiring repairs will be closer to around 300. However, this model has been adjusted to reflect damage during a single event (Sandy in 2012), and its performance and robustness needs to be tested with data collected after future storm events.

It is also important to consider that the damage descriptions above were based on visual inspections conducted by walking on the property: damage to below-ground components was not investigated, nor were the systems' hydraulic functionality or water quality renovation functions assessed. Therefore, systems that were assumed to be in working order because there was no visible above-ground damage may have in fact been functionally compromised by sediment influxes, dislodged pipes and/or destruction of other system components not visible from the ground surface (Scherer 2019; USEPA 2017). For example, sandy soils fluidized by flooding and/or elevated water tables may have filled void spaces in gravel-filled trenches in drainfields, affecting the hydraulic function of the system. Changes in void spaces in drainfields would not be visible from the ground surface. Furthermore, the notes from the Westerly field assessments also show that 62 of the systems in the area consisted of cesspools, which were required in 2007 to be replaced by advanced nitrogen removal systems, but had not been upgraded prior to the storm event (RIDEM 2007). Since cesspools tend to be deep buried pits which provide minimal treatment of wastewater (Amador and Loomis 2018), one can assume that during the flooding events of 2012 in the aftermath of Superstorm Sandy, untreated wastewater entered coastal drinking water aquifers and surface waters from these sites.

By comparison, Superstorm Sandy did not disrupt any of the three centralized wastewater treatment facilities' service to residents along the southern RI coast, as none of the systems stopped accepting wastewater. In Narragansett, RI, the storm surge flooded portions of the Scarborough Wastewater Treatment Facility, which serves an estimated 7,300 residences in Narragansett (RIDEM 2018b), and was without electricity for approximately five days. However, during this time the facility continued to accept wastewater, and poorly treated sewage overflowed into Narragansett Bay (Sullivan 2016), so the treatment performance of this facility was impaired. The facility has since been retrofitted with resiliency measures to protect it from future events (Woodard & Curran and RPS ASA 2017). In Westerly, several pump stations were without power in the aftermath of Sandy, requiring septage haulers to pump and remove wastewater from the stations to protect local homes and businesses (Sullivan 2016), but in these cases, residents were not affected, and presumably the wastewater was treated at the Westerly facility.

Testing of the model indicates that it tends to underestimate damage to systems, especially moderate and serious impacts, based on visual above-ground inspections (Table 3). The model is based on large-scale generalizations occurring along the coast that rely on several assumptions, which could be refined with better data inputs and validation. For example, a parcel's mean elevation is based on 60 cm (2 foot) contour lines; the accuracy of damage predictions would likely increase if the elevation of the actual system (rather than the whole parcel) were used. This is feasible, but would require geo-referencing of each individual system on each property, which would require a manual review of every OWTS permit application for each lot in the area, and a manual entry of the system's relative location on the parcel. Furthermore, incorporating surrounding landscape properties and localized relief, which are likely to shape the type of inundation (e.g., fast *vs* slow moving waters) at the parcel level, would also help improve model predictions. Additionally, using flood depth on each parcel, in addition to overall coast-wide flooding extents would likely result in a more refined model to be created, which might help explain the remaining differences between the observed damage and the model's predicted damage categories. Finally, accounting for long-term changes to groundwater tables in response to SLR and other human impacts to groundwater use and recharge in the area (Cox et al. 2019; Sukop et al. 2018; Walter et al. 2016) could improve the model's predictive power as well.

Future storm events, and detailed damage assessments in their aftermath will help refine the model to more accurately predict, on the parcel-scale, which OWTS are likely to be damaged to what degree. This requires a regulatory framework in the aftermath of such an event that collects detailed descriptions of the damage incurred and repairs performed to restore the system's function.

Implications

Improving this model's predictive power and accuracy will require more information on impacts to OWTS in the aftermath of storm events along the coast, which can be difficult to obtain. For example, there is little information available publicly that describes damages sustained during Superstorm Sandy, one of the largest events to affect the southern RI shore in the past few decades. As of now, RIDEM does not have systems in place to formally track future storm-related damages to coastal OWTS, or to monitor system repairs in the direct aftermath of a storm. The current approach – to expedite necessary repairs by allowing licensed or approved professionals to repair or replace at-grade advanced treatment components and above-grade soil treatment options in-place with in-kind materials in the aftermath of a severe storm (RIDEM 2012) – helps to get systems back into operating status more quickly than by following the usual repair application permitting process. However, it does not collect the types of data necessary to enable regulators or communities to understand the true impact to OWTS in their region, nor does it ensure that systems are functional, as there is no oversight of the repairs once completed per the current policy (RIDEM 2012). The policy post-Superstorm Sandy specifies that repairs should be documented and reported to RIDEM once completed (RIDEM 2012), but this information is not available at this time, raising questions about the efficacy of this approach.

Without a centralized approach to compiling and assessing storm-related impacts to OWTS, individual communities are left to address these issues on their own, which is problematic for several reasons: (1) not all coastal communities have active onsite wastewater management programs with sufficient staffing to assess impacts to OWTS and/or oversee their repairs; (2) data collected by individual communities according to their own procedures makes it difficult to integrate data across communities, requiring additional time and standardization of information before the data can be analyzed; (3) data collected by individual communities is not easily available to regulators (e.g. RIDEM staff) responsible for state-wide OWTS permitting and oversight. This issue could be solved by developing a centralized system that collects post-storm OWTS inspection reports, which could be generated by RIDEM personnel, local wastewater management program officials, and/or trained professionals. A well-designed, digital OWTS inspection questionnaire required to be submitted after any storm event surpassing a certain magnitude could provide critical, standardized data to stakeholders at the individual, community and state levels, overcoming the three problems with the current approach outlined above. These data would help stakeholders quantify damages to OWTS in a region, and could then be used to create a more refined model with better accuracy for predicting future impacts to systems along the coast. Integrating data from routine inspection and operation and maintenance reports into this database could help assess long-term impacts and performance of OWTS in these areas, helping communities understand how sea-level rise and storms affect systems over time, and whether there are spatial patterns of vulnerability stakeholders are currently unaware of.

The financial implications of storm impacts to OWTS are another important point to consider. The cost of repairing a damaged septic system can range from several hundred dollars to over \$15,000, depending on the complexity of the system and its components (Kevin Hoyt, personal communication 2019). Highly engineered systems that include multiple pumps, timers and a control panel, and/or above-ground drainfield designs will be more expensive to repair than passive conventional systems. Replacing a failed system with a conventional gravity-fed drainfield connected to a septic tank typically costs \$10,000 to \$18,000, whereas installing an advanced nitrogen-removal system (required in near shore areas by the RIDEM regulations; RIDEM 2018) usually costs from \$23,000 to over \$30,000 (http://www.dem.ri.gov/programs/water/owts/). Replacing just the 187 systems identified by the improved model in this study as likely to be seriously affected with the RIDEM-required advanced nitrogen removal technology could cost \$4.3 to 6 Million, though the original model's assumptions resulted in >400 systems being seriously affected, costing upwards of \$10 Million to replace.

In addition, the observations from personnel from the town of Charlestown indicate a significant difference in damage profiles for conventional OWTS with below-ground components and advanced nitrogen removal technologies: in many cases, buoyant pump tanks and other above-ground infrastructure and components of the advanced technologies sustained significant damage in areas subject to storm surge. Thus, while these technologies protect public and ecosystem health by reducing nitrogen loading to the region, they may be more vulnerable to storm events than conventional systems if they are not designed or installed with protective measures in place. This can be addressed by updating current regulations and by changes in industry standards and practices for advanced treatment systems installed in near-shore areas subject to storm surge.

Currently, there is no centralized geo-referenced map for OWTS in RI, nor is there an easy way to find what type of OWTS (conventional *vs.* advanced treatment) is on any given parcel or its location, without manual review of each individual permit application file. As discussed earlier, mapping each system's location on the parcel, in addition to information on the type and configuration would improve the model's predictive power, especially once post-storm inspection reports and data were integrated in the proposed database. This information could shed light on why OWTS on neighboring parcels are affected to drastically different degrees (Fig. 4), and suggest which other systems may be particularly vulnerable in future events, especially if more systems are upgraded to include apparently vulnerable advanced technology required in the region.

Finally, it is important to remember that an inspection of the physical components and their functioning is not an adequate assessment of an OWTS' overall function, even in normal conditions: advanced treatment systems not monitored for wastewater renovation performance have been shown to produce lower quality effluent than systems whose water quality parameters are used to recursively adjust and monitor systems until they are brought into compliance with water treatment standards (Amador et al. 2018; Lancellotti et al. 2017). None of the post-Superstorm Sandy OWTS observations included water quality parameter analysis, raising questions about apparently undamaged systems, and whether the storm event disrupted their ability to treat wastewater. Incorporating performance monitoring into assessments of systems along the coast might protect environmental quality and public health in near-shore areas, as above-ground surveys of system damage may fail to notice below-ground changes to relative elevations and other damage sustained during flood events, which could seriously compromise the system's ability to adequately lower nutrients and pathogen levels before wastewater enters groundwater and coastal water bodies.

A centralized tracking system of performance monitoring data, in addition to the proposed inspection report database could allow coastal communities to answer these questions and assess risks to public health and the environment from storm-affected OWTS in coastal regions in a data-driven manner. These data would further strengthen the model's ability to project both near- and long-term impacts – both in terms of structural damage and performance impairment – to OWTS for future storm events, and inform regulations and policy to ensure that these critical pieces of infrastructure function as intended in coastal communities.

Conclusions

Coastal hazards pose threats to coastal communities, however, current resilience plans may not be addressing OWTS as a major component of the water infrastructure in communities lacking centralized wastewater facilities. Modeling indicates that a large number of coastal OWTS (up to 2,000) on the south shore of Rhode Island might require repairs following a major flood event; something homeowners may not be aware of. Although the model in this study appears to underestimate damage 20% of the time, better data could leave to further model improvements, which could serve as a planning tool for communities preparing for a less certain future where recurrence intervals for major storm events decrease and SLR accelerates due to climate change.

The accuracy of the model applied in this study is limited to a large extent by the available data, highlighting the need for more detailed data describing post-storm impacts to OWTS. The model could be refined by including geospatial attributes (e.g., location of OWTS on individual parcels, microtopography surrounding OWTS, storm-related erosion and deposition patterns) and detailed descriptions of damage sustained by individual OWTS during and after storm events.

The current, decentralized approach in RI to assess damage to systems after a major storm event strikes the coast does not provide critical information to coastal communities, regulators or other stakeholders to inform holistic coastal resilience planning that must include OWTS as a critical component of the local infrastructure. Furthermore, above-ground visual inspections of post-storm damage may not be sufficient to protect local groundwater or coastal water resources, as septic system function may be compromised by flooding and dislodged below-ground components. The methods described in this study could be applied by any coastal communities with basic geospatial data available to them, and may help stakeholders make informed management and policy decisions to improve their communities' resilience to a changing climate. However, as the results of this study indicate, without a collaborative and consistent data collection approach in the aftermath of storms, or changes in design requirements to make coastal systems more resilient to storm events, many coastal communities could face chronic water quality problems related to pathogen and nutrient pollution of groundwater and coastal waters from OWTS compromised by storm events – perhaps even months or years after a hazard has damaged properties along the coast.

Acknowledgements

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Data Availability Statement

Some or all data, models, or code used during the study were provided by a third party: Descriptions of damage to OWTS in Westerly, RI in the aftermath of Superstorm Sandy provided by Peter O'Rourke of the RIDEM in 2019. Direct requests for these materials may be made to the provider as indicated in the Acknowledgments.

Some or all data, models, or code generated or used during the study are available from the corresponding author by request: (1) Damage descriptions for OWTS in

Charlestown, RI following Superstorm Sandy, (2) ArcMap maps and attribute tables for parcels affected by flooding for different storms. Other geospatial data is freely available through RIGIS (2017a) or town websites.

Supplemental Data

Fig. S1 and Table S1 are available online in the ASCE Library (www.ascelibrary.org).

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Table 1. Description of projected storm impact categories to OWTS along the southern RI coast.

Impact Category	Mean Parcel Elevation (m)		Impacts to System	Examples of Observed Damage
	Abutting Block Island Sound	Inland		
Serious	< 2	< 1	Major Repairs / Total Replacement Required	"fully exposed septic tank ocean side undermined, no outlet pipe, building sewer broken, covers off, tank full, likely destroyed" "tank seaward of dwelling, full of sand, building sewer and riser destroyed" "could not locate system likely destroyed, unknown, 2 destroyed tanks on beach west of dwelling" "septic tank in beach – system gone"
Moderate	2 – 2.4	1 – 1.2	Minor Repairs Required	"system in front, building sewer un-supported due to erosion, appears intact, system inundated, requires assessment" "building sewer requires assessment vertically pitched at direction of surge, inundated, no signs of breakage above ground. Apparent gray water pipe broken by surge at ground level, system inundated" "site affected by surge. Very heavy deposition, building sewer appears ok. Tank in rear appears ok. Gray H20 building sewer only may need repair"
Ephemeral	> 2.4	> 1.2	No Long-term Effects	"building sewer ok, system appears inundated but ok" "advanced N-removal technology, bottomless sand filter [drainfield] and electrical panel all appear ok and not visibly affected by surge" "system not visibly affected, appears ok" "no sign of system damage"

Mean parcel elevation was calculated by averaging 2-ft contours across parcels in ArcMap. Examples of observed damage obtained from Charlestown town officials and RIDEM personnel after Superstorm Sandy affected the southern RI coast in 2012 (Peter O'Rourke, personal communication, 2019).

Table 2. Summary of effects of different storm events and sea level rise (SLR) on OWTS, based on the updated model optimized with post-Sandy damage observations.

SLR (m)	Flood Type	Impact Category: Serious # Parcels	Serious % total†	Moderate # Parcels	Moderate % total†	Ephemeral # Parcels	Ephemeral % total†	Total # impacted Parcels	# Unaffected parcels	Elevation Range (m)
0	25-Y	187	4	63	1	2,809	61	3,059	1,573	0.6 - 9.1
0	50-Y	187	4	63	1	2,990	65	3,240	1,392	0.6 - 9.6
0	100-Y	187	4	63	1	3,194	69	3,444	1,188	0.6 - 9.7
0	500-Y	187	4	63	1	3,602	78	3,852	780	0.6 - 9.8
0	Hurricane Cat 1 (MAX)	187	4	63	1	1,789	39	2,037	2,595	0.6 - 9
0	Hurricane Cat 2 (MAX)	187	4	63	1	2,842	61	3,092	1,540	0.6 - 9.5
0	Hurricane Cat 3 (MAX)	187	4	63	1	3,667	79	3,917	715	0.6 - 10.8
0	Hurricane Cat 4 (MAX)	187	4	63	1	4,382	95	4,632	0	0.6 - 11.6
0.3	25-Y	187	4	63	1	3,000	65	3,250	1,382	0.6 - 9.7
0.3	50-Y	187	4	63	1	3,191	69	3,441	1,191	0.6 - 9.7
0.3	100-Y	187	4	63	1	3,369	73	3,619	1,013	0.6 - 9.7

†out of a total of 4,632 parcels possibly impacted by any storm event

Elevation range refers to the land elevations of parcels affected by flooding, based on flood maps (see Table S1).

Table 3. Comparison of model predictions and field observations of impacts to southern RI OWTS in the aftermath of Superstorm Sandy in 2012.

Descriptor	**Number of Systems**	**% of systems**
Total Systems with Observed Damage	345	100
Model Correctly Estimates Damage	235	68
Model Overestimates Damage	25	7
Model Underestimates Damage	68	20
Unable to Assess Model Estimate*	16	5

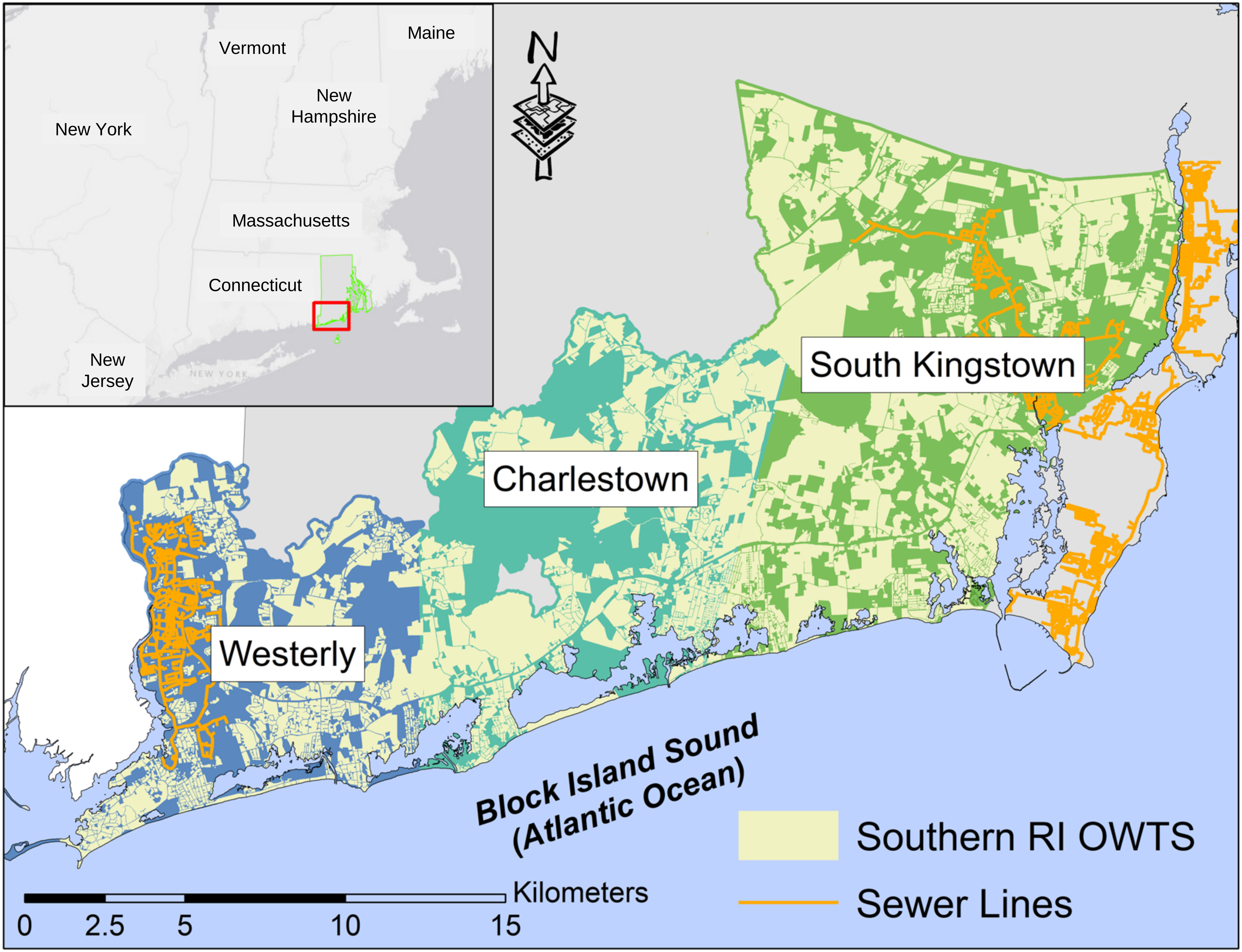
The total number of systems inundated (based on flood maps) was 2,334. 15% of these systems (n=345) were assessed visually in the field by Town of Charlestown officials or RIDEM personnel.

Figure 1. Map of the southern RI parcels relying on OWTS. The blue region south of the coast is Block Island Sound. The orange lines indicate location of sewer lines. Blue, teal and green shaded regions represent parcels which do not have OWTS in Westerly, Charlestown and South Kingstown, respectively. Service layer credits: Esri, HERE, Garmin, © OpenStreetMap contributors and the GIS user community.

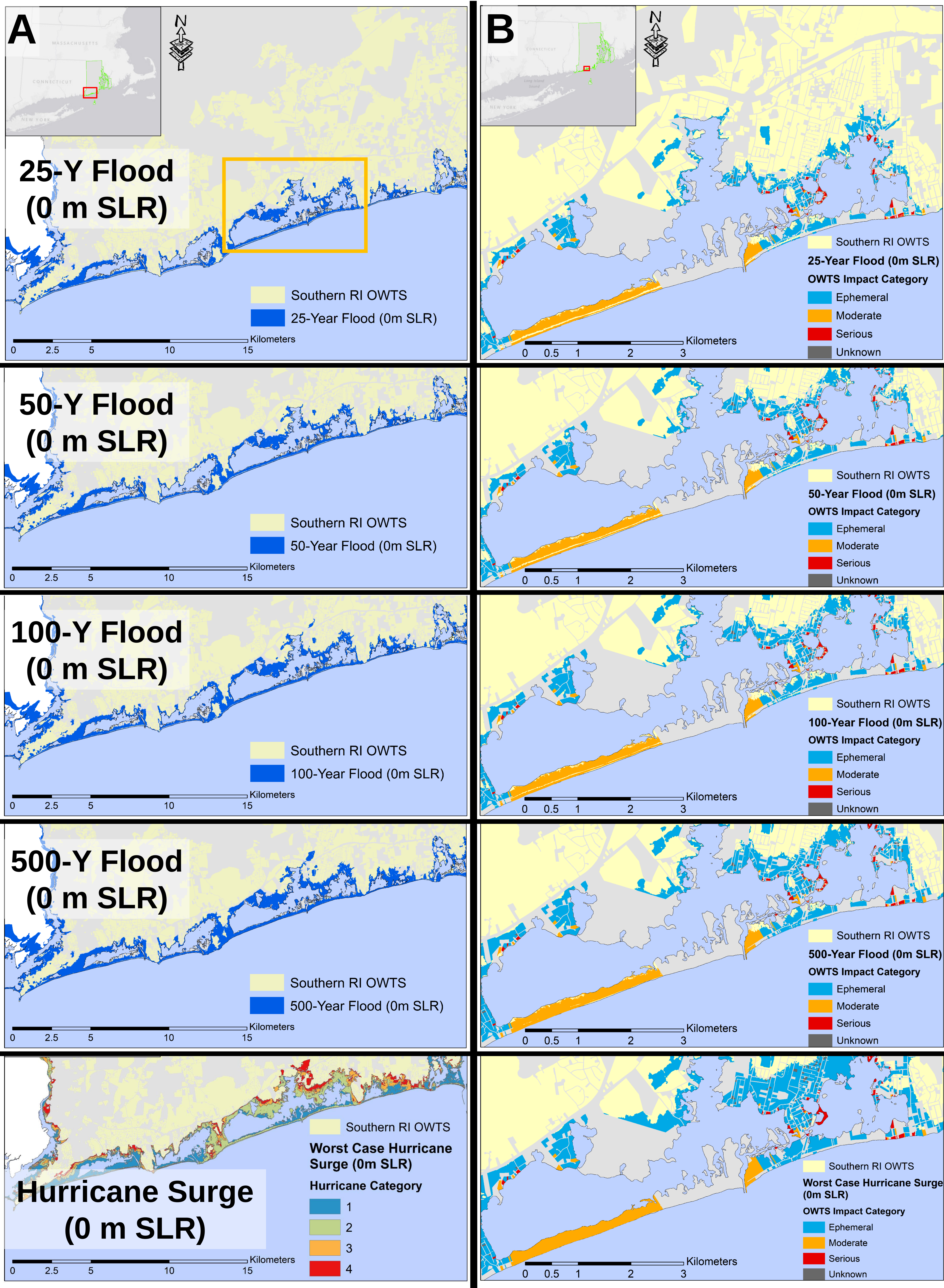
Figure 2. Panel A: Flooded regions of southern RI, based on 25-Y, 50-Y, 100-Y, 500-Y Flood Events and Worst Case Hurricane Scenarios with 0 m sea level rise (RIGIS 2016b). *Orange box in top panel indicates the extent of maps on right-hand panels (B). Grey regions in the map represent unbuilt parcels without OWTS. Panel B: Extent of a subset of OWTS affected by storm events of varying magnitudes under current conditions (0 m sea level rise). Systems in red are predicted to be seriously impacted, while those in orange are projected to bear moderate damage, and blue-colored parcels face ephemeral damage (Table 1). Service layer credits: Esri, HERE, Garmin, © OpenStreetMap contributors and the GIS user community.*

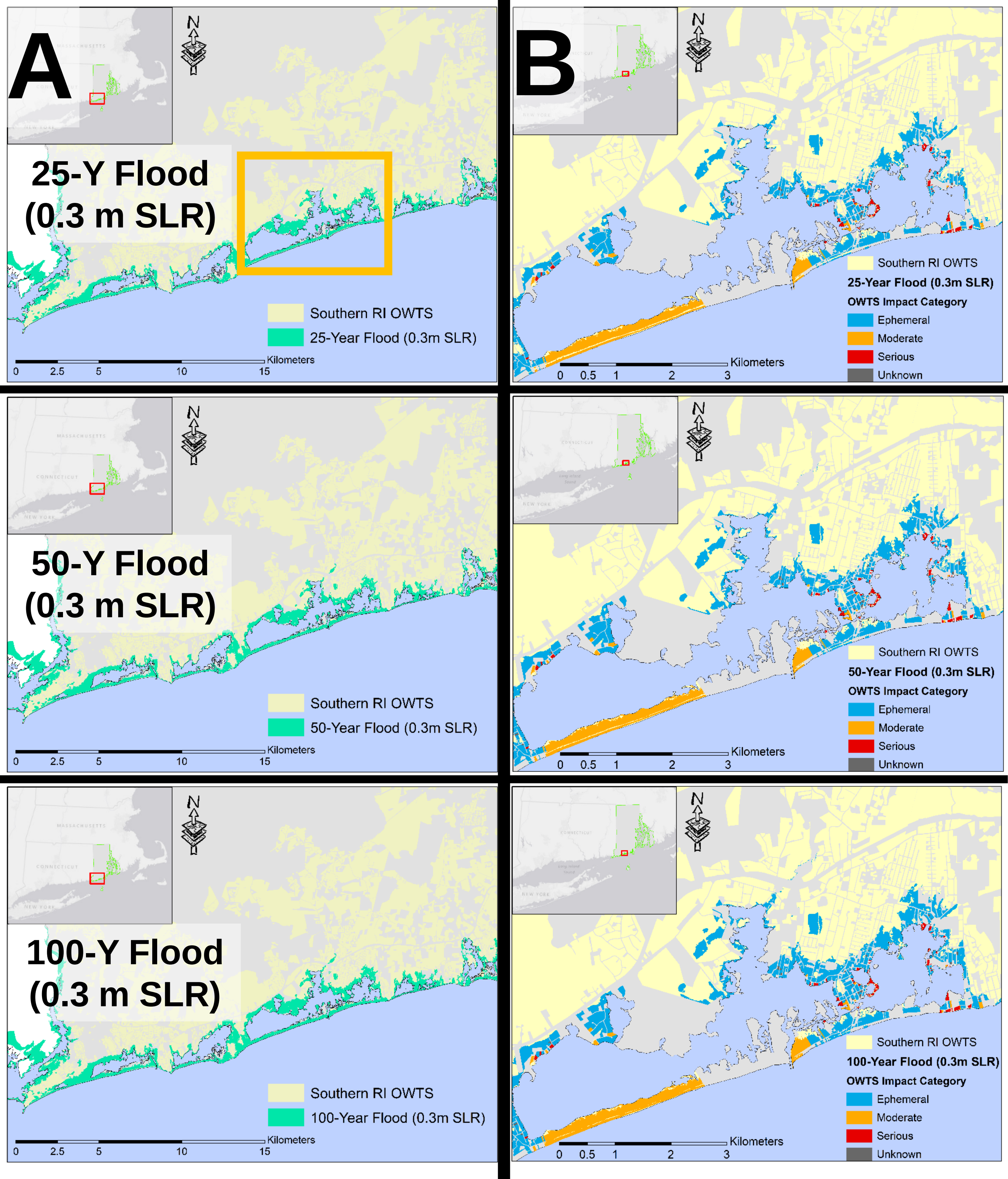
Figure 3. Flood maps (A) and extent of associated OWTS damage (B) for 25-Y, 50-Y, and 100-Y Flood Events with 0.3m sea level rise. Modeled system locations and numbers are based on 2018 data and assume no additional development. Orange box in top panel indicates the extent of maps on right-hand panels (B)s. Systems in red are predicted to be seriously impacted, while those in orange are projected to bear moderate damage, and blue-colored parcels face ephemeral damage (Table 1). Service layer credits: Esri, HERE, Garmin, © OpenStreetMap contributors and the GIS user community.

Figure 4. Testing the improved model of damage to OWTS after Superstorm Sandy struck the southern RI coast in late October, 2012. Panels A and B represent areas in Charlestown, RI; data from lower panels of C and D in Westerly, RI were provided by Peter O'Rourke (personal communication, 2019). Service layer credits: Esri, HERE, Garmin, © OpenStreetMap contributors and the GIS user community.

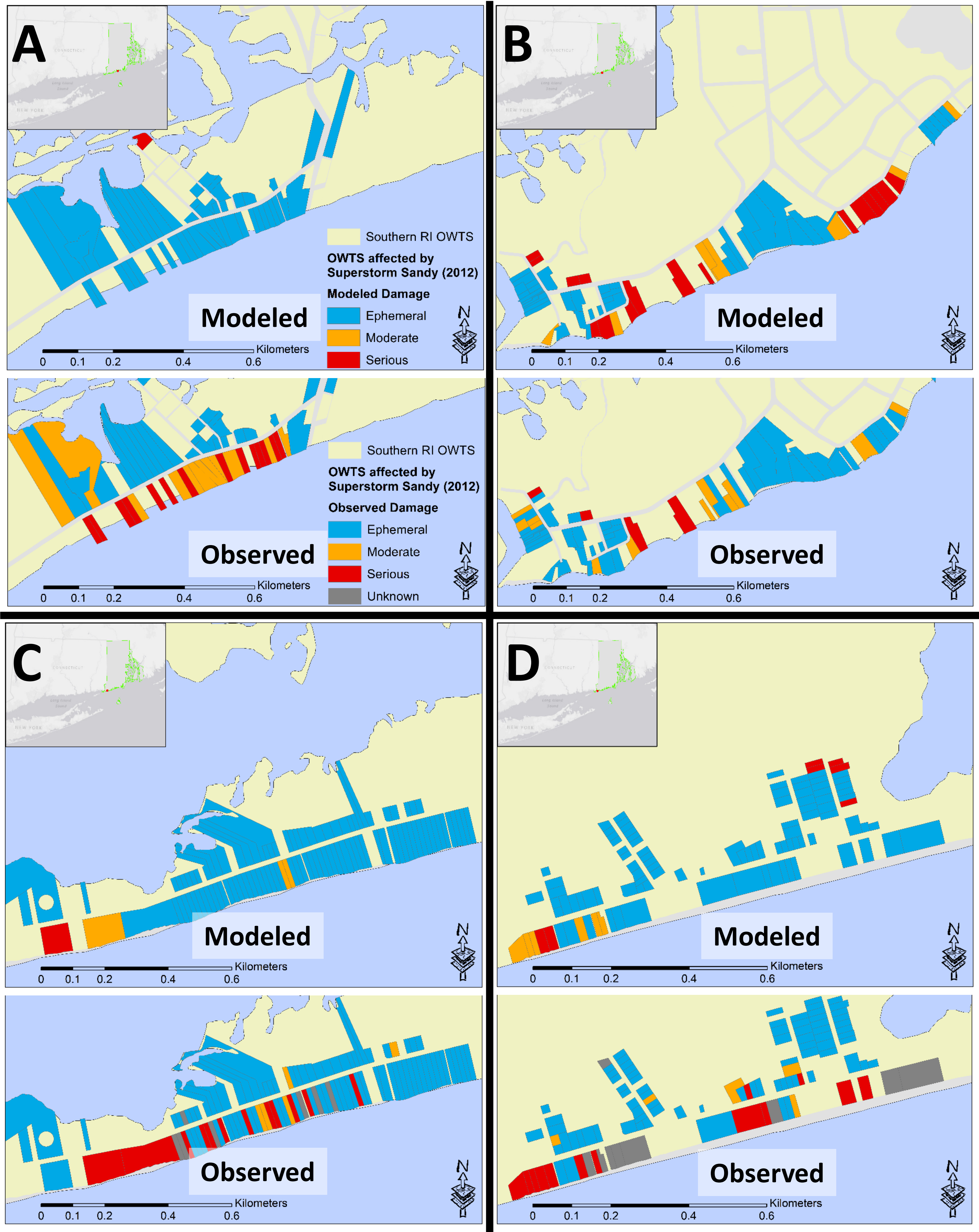


Vermont
Maine
New Hampshire
New York
Massachusetts
Connecticut
New Jersey
NEW YORK
N
South Kingstown
Charlestown
Westerly
Block Island Sound
(Atlantic Ocean)
Southern RI OWTS
Sewer Lines
Kilometers
0
2.5
5
10
15


A
25-Y Flood (0 m SLR)
Southern RI OWTS
25-Year Flood (0m SLR)
Kilometers
0 2.5 5 10 15
B
Southern RI OWTS
25-Year Flood (0m SLR)
OWTS Impact Category
Ephemeral
Moderate
Serious
Unknown
Kilometers
0 0.5 1 2 3
50-Y Flood (0 m SLR)
50-Year Flood (0m SLR)
100-Y Flood (0 m SLR)
100-Year Flood (0m SLR)
500-Y Flood (0 m SLR)
500-Year Flood (0m SLR)
Hurricane Surge (0 m SLR)
Worst Case Hurricane Surge (0m SLR)
Hurricane Category
1
2
3
4
Worst Case Hurricane Surge (0m SLR)



A
B
25-Y Flood
(0.3 m SLR)
50-Y Flood
(0.3 m SLR)
100-Y Flood
(0.3 m SLR)
Southern RI OWTS
25-Year Flood (0.3m SLR)
50-Year Flood (0.3m SLR)
100-Year Flood (0.3m SLR)
OWTS Impact Category
Ephemeral
Moderate
Serious
Unknown
Kilometers
0 2.5 5 10 15
0 0.5 1 2 3
N



A
B
C
D
CONNECTICUT
NEW YORK
Long Island Sound
Southern RI OWTS
OWTS affected by Superstorm Sandy (2012)
Modeled Damage
Ephemeral
Moderate
Serious
Observed Damage
Unknown
Modeled
Observed
N
Kilometers
0
0.1
0.2
0.4
0.6

Geospatial modeling suggests threats from stormy seas to Rhode Island's coastal septic systems

Alissa H. Cox*[1], Matthew J. Dowling[2], George W. Loomis[3], Simon E. Engelhart[4], Jose A. Amador[5]

*Corresponding author: alibba@uri.edu

[1]*Department of Natural Resources Science, University of Rhode Island, 1 Greenhouse Rd, Kingston RI 02881, USA; alibba@uri.edu*

[2]*Town of Charlestown, RI, Wastewater Management Division, 4540 South County Trail, Charlestown RI 02813, USA; mdowling@charlestownri.org*

[3]*New England Onsite Wastewater Training Center, University of Rhode Island, 1 Greenhouse Rd, Kingston, RI, USA; gloomis@uri.edu*

[4]*Department of Geography, Durham University, South Road, Durham DH1 3LE, UK; simon.e.engelhart@durham.ac.uk*

[5]*Department of Natural Resources Science, University of Rhode Island, 1 Greenhouse Rd, Kingston RI 02881, USA; jamador@uri.edu*

Supplemental Material

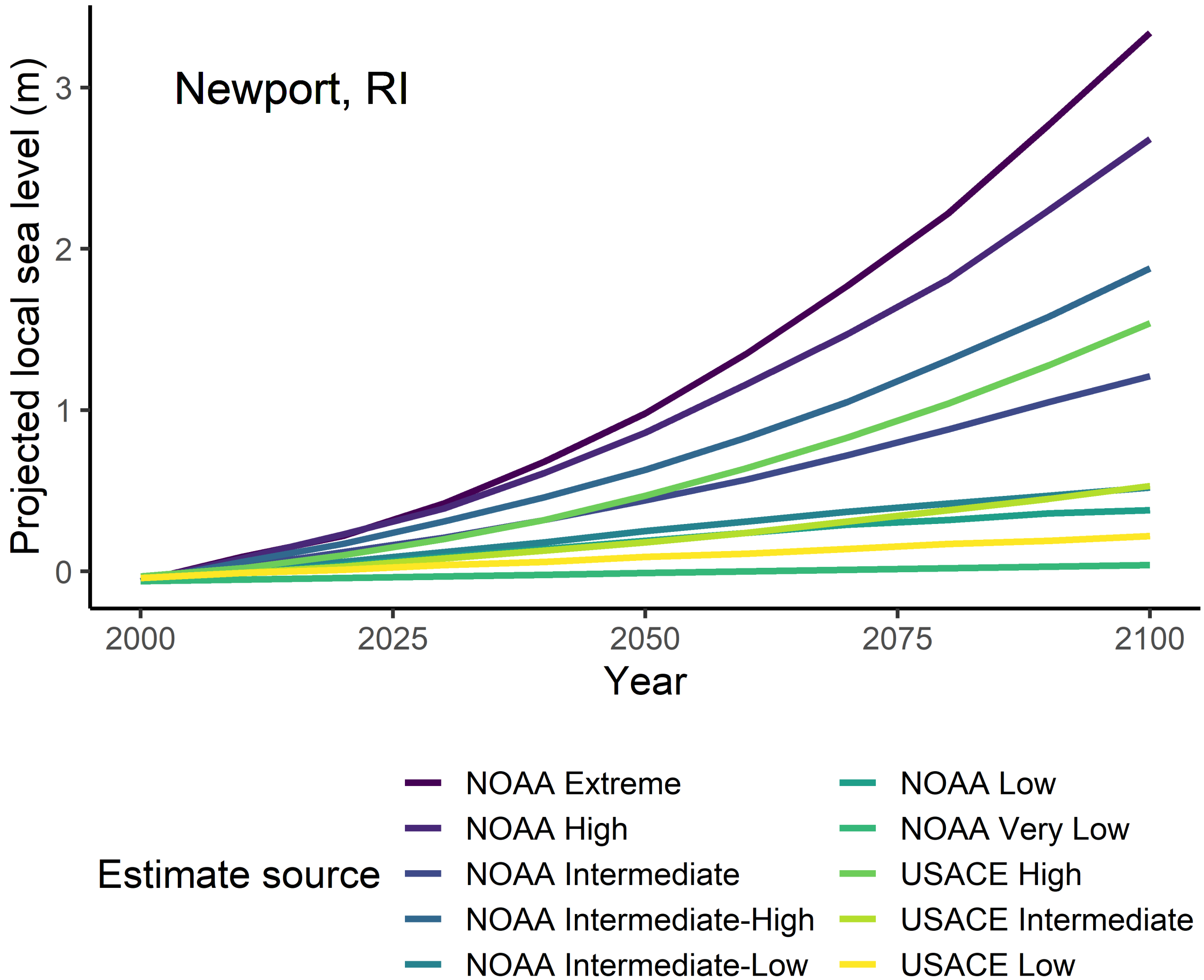


Figure S1. Sea level projections in Newport, RI for the 21st century. Projection estimates derive from NOAA and the U.S. Army Corps of Engineers (USACE) (NOAA et al. 2017; US Army Corps of Engineers 2019).

Table S1. Sources of GIS layer data used in analysis.

GIS Layer Name	Source	Website / URL	Date Downloaded
Charlestown Parcels (shapefile)	Town of Charlestown	http://charlestown.mapxpress.net/ - download "ESRI shapefile"	August 20, 2018
South Kingstown Parcels (shapefile)	Town of South Kingstown	Contact Carol Baker (cbaker@southkingstownri.com) for access	August 18, 2017
Westerly Parcels (shapefile)	Town of Westerly	http://gis.westerlyri.gov/portal.asp - download "Assessor Data"	August 19, 2017
Contour Lines: 2 Foot	RIGIS	http://www.rigis.org/datasets/d41a4de188ee44908a75d9911a90f4ce_0	November 20, 2017
Sewer Lines (shape file)	RIGIS	http://www.rigis.org/datasets/sewer-lines	November 17, 2017
Hurricane Surge Inundation (Worst Case) for Washington County	RIGIS	http://www.rigis.org/datasets/ae97019cb46446d485d45f8bac0cfc58_0	November 9, 2017
Inundation Polygons: Major Event, 25-year with 0ft SLR	RIGIS	http://www.rigis.org/datasets/inundation-polygons-major-event-25-year-with-0ft-slr	November 9, 2017
Inundation Polygons: Major Event, 50-year with 0ft SLR	RIGIS	http://www.rigis.org/datasets/inundation-polygons-major-event-50-year-with-0ft-slr	November 9, 2017
Inundation Polygons: Major Event, 100-year with 0ft SLR	RIGIS	http://www.rigis.org/datasets/inundation-polygons-major-event-100-year-with-0ft-slr	November 9, 2017
Inundation Polygons: Major Event, 500-year with 0ft SLR	RIGIS	http://www.rigis.org/datasets/inundation-polygons-major-event-500-year-with-0ft-slr	November 9, 2017
Inundation Polygons: Historic Storm, 2012 with 0ft SLR	RIGIS	http://www.rigis.org/datasets/inundation-polygons-historic-storm-2012-with-0ft-slr	October 30, 2018